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BIPROPELLANT VALVE IMPROVEMENT PROGRAM
APOLLO SERVICE PROPULSION SYSTEM ROCKET ENGINE
GUIDE FOR BIPROPELLANT VALVE DESIGN

Prepared Under
Contract NAS 9-8317

for

MANNED SPACECRAFT CENTER
National Aeronautics and Space Administration
Houston, Texas

Design Report 8317-D

June 1970

AEROJET LIQUID ROCKET COMPANY
A DIVISION OF AEROJET-GENERAL
SACRAMENTO, CALIFORNIA

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FIGURE LIST

I. SUMMARY

This is a special design report submitted in partial fulfillment of Contract NAS 9-8317, the Bipropellant Valve Improvement Program. The object of the report is to compile the results of the program studies emphasizing the application of these results to valves in general.

It has been found at Aerojet that the specific application requirements as well as basic design characteristics of various valve types control the design of valves. For this reason it would be impossible to compile in any one document a step-by-step guide which would satisfy any and all design requirements. Consequently, the approach taken herein has been to discuss design goals and requirements from a general viewpoint with the objective of familiarizing the reader with a method of approach and common practices. Included are: (1) generalized propellant valve design criteria along with recommended practices, (2) discussion of commonly encountered practical development problems, effects on design and recommendations for solutions, (3) a review of experience in propellant valve design, manufacturing and test, and (4) a discussion of tradeoff analysis along with the tradeoff analysis conducted as a part of the bipropellant valve improvement program. The general discussion is supported by a complete list of references and a bibliography.

Since the Apollo SPS bipropellant valve is used with earth storable propellants, primary emphasis has been placed on valves for this use. However, consideration of other propellants has been made where it was felt it would be beneficial, primarily in the generalized valve design criteria.

The primary objective of Contract NAS 9-8317 was the development of an improved SPS bipropellant valve. The techniques used to achieve this objective fall within the category of normal good design practice and no key design factors were developed which would have universal application. The successful

I, Summary (cont.)

demonstration of the modular design and the cam lifted seal did afford insight into several grey areas: This insight forms the basis for the following observations. The modular design did not result in a weight or envelope penalty, the cam lifted seal had significantly better life cycle characteristics than the rubbing seal, the cam lifted seal was still susceptible to particulate contamination; therefore, cleanliness during fabrication should be maintained, and if bellows type seals are used it is probably better to accept an envelope penalty to assure sufficient active convolutions and seal seating freedom rather than maintaining envelope and thereby restricting motion due to a stiff bellows.

The information presented herein was obtained primarily from within the Aerojet Sacramento Facility; however, information obtained in discussions with personnel of TRW Inc. and Bell Aerosystems Inc. has been included.

II. GENERALIZED PROPELLANT VALVE DESIGN CRITERIA

A. VALVE ASSEMBLY TYPE SELECTION

Valve assemblies are utilized in all liquid rocket engine systems requiring a variable flow control device. The valve assembly is defined as any device which stops, starts, or otherwise regulates the flow of a fluid by means of a movable valving element that either opens or obstructs a flow passage.

In this discussion all of the valve assemblies used in liquid rocket propellant systems are included. Individual valve components will be considered only to the extent necessary to support information regarding the entire valve assembly. Valve types include ball, butterfly, poppet, gate, blade, diaphragm, slide, and plug valves. An appropriate evaluation of actuators is included to show the interaction between the valves and the actuators.

The preferred type of valve assembly for various applications are identified along with the criteria that experience has shown is needed to assure the proper selection of valve components for an optimum design. Emphasis is placed upon the need for a comprehensive review of all design criteria if a design is to be truly optimum for a specific application. The need for considering trade-offs is stressed. For example, if zero seat leakage is of prime importance in a system where all other criteria indicate the use of a ball valve, the final selection most probably would be a poppet valve because of its higher poppet-to-seal loading; a slightly higher valve pressure drop could be a justified trade-off to obtain zero seat leakage. A preliminary trade-off study can be accomplished using Figures 1 and 2. Those figures represent a very basic comparison of the features of the commonly used valve types and actuator types and are included as a guide for the engineer inexperienced in valve technology. An example of a more thorough trade-off study is presented and discussed in Section V herein.

II, Generalized Propellant Valve Design Criteria (cont.)

B. VALVE CRITERIA

The selection of a valve assembly for a particular application results from a detailed analysis of the specific application requirements as well as the basic design characteristics of potential valve types. In the classic sense, this analysis is a systematic form of compromise wherein advantages and disadvantages of the different valve types are weighed against the specific requirements to permit an optional selection. This common approach to valve selection is basic to almost every design situation. Thus, it is readily apparent that the process is only as effective as the basic design criteria utilized to provide for consideration of all significant design factors. Any oversight in a basic design criterion can easily result in selecting a non-optimum valve type with subsequent development problems. Some of the more significant criteria for selecting a valve type are discussed in the ensuing sections.

1. <u>Flow Media</u>

The flow media is a basic design criterion and is a major factor in selecting the type of valve to be used. However, since flow media is only one of the factors which must be considered in the selection of a valve design it is not possible to consider any one valve type as superior for a particular flow media without knowing the effects of the other design environments and completing a trade-off study. Knowledge of the flow media (liquid, gas, or two-phase fluid) is essential because valve types vary in sealing capability with the fluid state. For example, a poppet valve generally will seal a light gas (i.e., helium) better than a butterfly valve. Additionally, the velocity of the media also must be examined because the flow of gases can erode seals. In selecting a valve type for an application where erosion can occur, consideration must be given to how well the main seat

or sealing surfaces are protected from this erosion. This is particularly true for hot gases or highly-reactive gases (i.e., fluorine). In considering the flow media, material compatibility is of basic concern because material restrictions resulting from use of a particular fluid could preclude consideration of a particular valve type. Flow media also can limit the valve types that can be considered as a result of contamination or the abrasive qualities of the medium. For example, a valve design with inherently low sealing forces and significant rubbing action would not be a desirable design selection for a slurry medium. Flow media also must be considered in terms of freezing point and whether entrapped fluid could subsequently freeze, resulting in high expansion pressures or damage caused by icing effects. Also thermal expansion of the fluid due to engine soak-back can result in high pressures.

2. Pressure

Pressure is a basic design criterion in selecting a valve type. Operating pressure not only establishes the basic structural requirements for the valve design, but eliminates some valve types from consideration. For example, use of a gate-valve in a particular system may not be feasible because of its unbalanced pressure characteristics and the large actuation forces resulting from the desired operating pressures (Reference 1). Similarly, the use of a ball valve or butterfly valve in a large line size (greater than 3 inches in diameter) may result in prohibitive bearing loads, seal loads, and actuation forces. The operating pressure also must be examined from the transient aspect as well as the static condition. If a valve design is susceptible to pressure damage in the intermediate open positions, the opening or closing transient pressure could cause seal failure. Should the operating pressure be compatible with the valve type in terms of structural strength for static as well as transient conditions, the number of

times that the pressure will be applied also must be considered. Repeated cycling of pressure upon a valve assembly can result in fatigue failures. In general, the valve types more suitable for higher pressures are the poppet, ball and butterfly, with the gate, blade and diaphragm designs more suitable for low pressure applications.

3. Flow Rate and Pressure Drop

Flow rate and pressure drop must always be considered in valve selection. The required flow rate and the maximum allowable pressure drop will establish the required size for each of the valve types. Once the size requirement for each type valve is established, several valve types generally can be eliminated from consideration. For example, the use of a butterfly valve in a 1-in. line size or smaller system is impractical because of its high pressure drop characteristics which result when it is reduced to this size. Conversely, the use of a ball valve in large line sizes may be impractical because of the resultant valve weight (Ref. 1). Valve type selection also is affected by whether or not the flow rate is a steady-state requirement (i.e., in a shutoff valve) or a variable requirement, (i.e., in a throttling valve) because some valve types have limited suitability as regards application. Generally, this is true of ball valves, gate valves, and blade valves (Ref. 1). The transient flow characteristics of a shutoff valve during the opening and closing cycles could impose further limitations upon its use in a specific application. It is not practical to list the range of pressure drops and flow rates associated with each valve type since those can be varied considerably by design details. It is more significant to be aware of pressure drop and flow rate as a design criteria and to conduct a detailed analysis of those factors during the preliminary design phase.

II, B, Valve Criteria (cont.)

4. Leakage

Leakage must be considered in terms of both internal leakage and external leakage. The more stringent the leakage requirements, the more difficult and costly it will be to achieve success. For example, an unrealistic, low leakage limit could eliminate consideration of the optimum type of valve. Leakage limits should be established as the most realistic values that will prevent depletion of the fluid, excessive loss of pressure, damage to the rocket system or equipment, danger to personnel, or failure of a mission objective. Once it is assured that reasonable leakage limits have been established, the various types of valves can be evaluated based upon their inherent sealing capabilities. An important consideration in this evaluation is the great variance in leakage rates resulting from design details and cycle life (Ref. 2). The relative sealing capability of the various types of valves require thorough examination in relationship to the cycle life of the intended application.

5. Life

Each valve type requires evaluation in terms of the cycle life and storage life needed for the intended application. The cycle life is defined as the maximum number of operations (open and closed or through the throttling range) required that can be accomplished without exceeding any of the basic sealing or functional requirements for the valve assembly. To adequately evaluate the valve types in terms of cycle life capability requires a thorough knowledge of the state-of-the-art because cycle life for a particular valve type varies radically as size or test parameters (i.e., temperature, pressure, actuation rate, and fluid media) are altered. In addition, cycle life varies greatly within a valve type as a result of design details (i.e., seal loads, seal materials, seal shapes, and seal retention). In

addition to the criteria related to the total number of required cycles and the total storage life, the valve duty cycle requires examination. This consists of establishing when cycling is required during the life of a valve as well as whether or not the valve is dry or exposed to the flow media during any idle periods. Proper design also calls for an evaluation of what effect the duty cycle has upon the cycle life for each of the valve types under consideration.

6. Other Design Criteria

The preceding five design criteria are the most obvious factors to be considered when selecting a valve assembly design. A number of other factors also require consideration. The valve response and environmental requirements are typical of these. If a fast acting valve is required, a valve type in which the moving member has a large inertia high force requirements, or long travel may not be suitable (i.e., gate and blade valve designs). The operating temperature range restricts the use of various seal materials and results in further limiting the potential valve types. For example, sealing of hot gases cannot be accomplished using plastics or elastomers and sealing of cryogenic fluids must consider the material properties at low temperatures. Although those factors may be primarily limitations upon seal material selection, both of these factors may limit the potential valve types for a particular application. Temperature also can influence design selection from a transient aspect because the use of some valve types is not desirable where thermal shock is involved or where sealing is required while the valve experiences a change in temperature. The valve environment also must be considered with respect to vibration, acceleration, and shock levels. This is particularly important in selecting the valve and actuator combination.

II, B, Valve Criteria (cont.)

Exposure to vacuum and the requirement for sterilization constitute additional design criteria. Vacuum exposure limits sealing techniques by restricting the use of materials. It also affects design selection by restricting the use of lubricants because many lubricants will boil-off at hard-vacuum levels. If the application requires sterilization of the valve, the ease of sterilization must be considered along with the compatibility of the design with the materials used for sterilization (i.e., Zephiran, Ceeprin, or ethylene oxide). The necessity for removing the flow media to allow for safe handling or storage also must be examined. If a valve is to be utilized in toxic fluids, the basic design must provide for adequate fluid removal to allow safe handling during rework or use (Ref. 3). A need for the complete fluid removal could exist as a result of using corrosive or highly-reactive fluids having limited times that the valve elements can be exposed to them.

C. ACTUATOR CRITERIA

The design of the actuator must be considered concurrent with the basic valve design. Selecting the proper actuator type during the initial valve design phase can result in reduced envelope size and over-all weight as well as optimum integration of the valve and actuator.

The most common actuators used in chemical rocket propulsion systems are the pneumatic, hydraulic, and electrical types. Generally, pneumatic and hydraulic actuators are of the piston type, directly connected to the valving element or interconnected by means of a mechanical transmission (i.e., gears, screwjacks, rocker arms, and torque tubes). Electrical actuators usually are directly-connected solenoids or electric motors that are connected by a method of transmission similar to that for the pneumatic and hydraulic actuators.

Designing an actuator and integrating it into a valve assembly becomes complex because of the many mechanical, operational, and environmental conditions to be considered. Generally, the final actuator design evolves from a series of design trade-offs which proceeds until all conditions are satisfied. The factors and conditions involved in the selection and design of a valve actuator are discussed in the following sections.

1. Energy Sources

The most convenient actuator energy source would be the power available from an existing engine system; i.e., propellant, hydraulic, hot gas, or cold gas pressures, or engine electrical power (Ref. 4). However, available systems often will not provide the performance required at the critical time; propellant pressure could be insufficient or pressure drop could occur as the valve opens, hot gas pressure is unavailable until after the valve opens, and electrical power could be limited, to mention but a few. The use of hot gases presents problems in component tolerances and fits as well as in material selection. Icing, poor actuator control resulting from "gassing-off", and critical tolerances as well as fits could be problems when cryogenic fluids are used. Even storable propellants, used at normal temperatures, can freeze during venting requiring heaters on the actuator and vent line. A problem of this type was experienced with the Transtage engine bipropellant valve assembly and electric heaters were incorporated to eliminate it (Ref. 5).

When the use of available power proves unsatisfactory, an additional source of power must be supplied. A pneumatic actuation system (including a pressurized gaseous nitrogen tank, shut-off valve, regulator, relief valve, and pilot valves) was incorporated into the Apollo SPS engine bipropellant valve and engine design. In other situations, a complete hydraulic system might have to be added to the engine system while for "one-shot" service, an explosive squib could be satisfactory.

II, C, Actuator Criteria (cont.)

2. Force and Travel

A valve actuator must generate sufficient force to overcome all resisting loads (i.e., friction, pressure forces, component inertias, and return spring forces) and must have sufficient reserve force to cope with extraneous loads caused by icing, possible tight fits resulting from extreme temperatures, and other conditions. In low pressure or low voltage applications, the size of the actuator could become larger than the specified valve envelope size. In this situation, a smaller actuator with a longer travel could be connected to the valving element through a mechanical device to obtain a mechanical advantage as well as the desired result. In hydraulic and pneumatic systems, the final design frequently is a trade-off between a large diameter, short stroke design and a small diameter, long stroke design. The generally available power in chemical rocket propulsion systems is 28 vdc which limits the design of electrical actuators to within this voltage availability.

Consideration must be given to the effect of variable actuation force throughout the actuator travel range. A high break-away load caused by the seal set is encountered during the initial actuator movement. As the valving element approaches its operating range or full-open position, fluid forces can act upon the element tending to open the valve even further or restraining the opening travel. Actuators designed for throttle valves and other valves operating in the mid-range of actuator travel require good holding capability. These actuators should be free from drift and capable of holding a programmed position; the best type of actuator for this function would utilize a screwjack for power transmission or an incompressible fluid as the actuation medium. Actuators must have sufficient power to overcome all of the forces discussed in this section plus sufficient margin to ensure repeatable operation.

II, C, Actuator Criteria (cont.)

3. Response Time

Response or travel time is that time required for the actuator and valving element to move through the opening or closing excursion. Signal time is the delay time experienced from the initiation of the excursion signal to the start of actuator movement. Total (excursion) time is defined as signal time plus travel time.

The response time of electrical actuators is governed by the solenoid or motor design and usually is fast as well as highly repeatable. Pneumatic and hydraulic actuators generally are over-powered to ensure rapid operation and the response time is controlled by orificing the fluid medium. The travel time of valves used in propulsion systems is critical and must be repeatable within specified limits. The signal time span might not be critical as long as it is repeatable from one actuation to another.

4. Life

Actuators installed in propulsion system valve assemblies must be designed for operation in earth and space environments over a significant time span. The design must withstand all operational and environmental conditions over this time span while operating satisfactorily throughout the operational period. An adequate power source (i.e., gaseous nitrogen and electrical current) must be available to ensure proper valve operation throughout the specified period. Auxiliary power sources could be required to supplement the normal supply during extended missions. Consideration must be given to the size of the actuator, the type and size of seals, the kinds of lubricants, and other design criteria in selecting an actuator for a specific application. The cycle life of each type of actuator varies as it is influenced by the specific operating environment and its details of design and construction.

II, C, Actuator Criteria (cont.)

5. Environment

Environmental conditions of launch and flight operations must be considered for their effects upon the functional reliability of the actuation system. These environmental conditions include temperatures, pressures, vibration, radiation, acceleration loads, vacuum (storage in space), sunshine, and others. For example, extreme temperatures will affect the selection of materials, fits and tolerances, trapped fluid pressures, lubricant viscosities, solenoid and electric motor coil resistances, and other design factors. Considerations must be given to these problems as well as to all other environmental-caused problems in the design criteria as well as the type of actuator selected.

D. VALVE-ACTUATOR INTEGRATION

Consideration must be given to the integration of the different types of actuators into the complete valve assembly. Some of the methods of mechanical transmission are direct-connected pistons and solenoids, rocker arms, gears, push-pull rods, cams, cam and gear, toggle link, worm gear, and ball screw. Interactions between the actuator and valve (i.e., side loads and dynamic response) must be considered. The problems of creating a balanced valve for reduced actuator loads must be considered in relation to the reduction in power requirements obtained.

Some of the typical applications to be considered are those concerned with converting linear motion of an actuator to rotary motion of the valve as well as provisions for an actuator to hold a position when subjected to a variable load. The methods for achieving these applications require numerous considerations and trade-offs. For example, when converting linear motion to rotary motion, a rack and pinion or mechanical linkage method can be

II, D, Valve-Actuator Integration (cont.)

used. Areas for consideration should include the use of rack and pinion for long stroke and the mechanical link for short stroke as well as the use of an idler back-up for the rack to ensure proper gear engagement and reduce side loads in the actuator shaft. When the mechanical linkage methods are utilized, consideration must be given to link length and bearing size to prevent binding. When locking actuators are required, the methods to be considered include screw output actuators, hydraulic actuators, and pin and ball locks which are spring or piston actuated.

E. OTHER DESIGN FACTORS

There are many design considerations that have applicability regardless of valve type, actuator type, or method of integration. Typical of these are the envelope, weight, cost, ease of fabrication, maintainability, and decontamination. Although these are not operational criteria, they are highly significant, sometimes overriding functional criteria in trade-offs. Areas affected by these factors must be identified so that they can be treated during preliminary design. Some illustrative examples follow:

- A valve used with a toxic propellant might require subsequent flushing with neutralizing fluids. The design must provide passages and access ports for the flushing media even though this makes the envelope larger and the valve more complex.

- A minimum weight valve usually is required for propulsion system applications. For this reason, dissimilar metals, even though they have the potential for galvanic action, are sometimes used in a valve assembly. For example, an

II, E, Other Design Factors (cont.)

aluminum valve body might be used with adjacent, internal, stainless steel parts rather than also making the body of the relatively heavy stainless steel.

- A valve can be designed for welded inlet and outlet ports providing a compact, leakage-free package. If maintenance requirements necessitate removal without special tools, the valve will have to be larger to incorporate flanges and seals.

Recognition of some highly weighted criteria during preliminary design can aid in subsequent trade-off decisions. Considering the last two examples above, the designer could use a stainless steel body primarily to permit welding to the mating lines. Recognizing that a separable joint will be used could assist in making a decision to use an aluminum body and save weight.

III. PRACTICAL DEVELOPMENT PROBLEMS AND SOLUTIONS

The following paragraphs discuss the problem areas normal to a development program. The solutions to all of these problems are considered to be standard, good design practices; however, experience has shown numerous instances in which the interesting or unusual design aspects receive primary emphasis at the expense of the routine.

This section has been compiled in a checklist format to assist the designer or participant in a design review in making a methodical evaluation of a new design.

The criteria shown underscored in this section provide explicit statements of particular conditions, requirements, or standards for valve assemblies used in liquid rocket propellant systems and should be followed unless exceptions are dictated by the requirements of a specific application. The recommended practices shown in the lower case letters following each criterion are offered as those practices that will satisfy the criterion and assure a more expeditious as well as optimal preliminary design.

A. OPERATING CONDITIONS AND ENVIRONMENT

1. The Operating Conditions and Environment for the Valve shall be Derived from the Intended Engine Usage and shall become the Basis for the Valve Design

Conditions that should be specified and included in the valve design and analysis are:

a. Rated working, maximum working, maximum design, proof, burst, and leakage pressures

b. Pressure drop and flow rate

III, A, Operating Conditions and Environment (cont.)

c. Flow media (including expected contamination levels)

d. Allowable leakage (internal and external)

e. Operating temperatures

f. Duty cycle requirements (maximum and minimum number of cycles, storage life)

g. Environment

2. The Environments (Loads, Stresses, Thermal Profiles, Radiation, Vacuum) Imposed by both the Valve and Next Assemblies shall be Specifically Considered in the Mechanical Design

A continuous upgrading of environment predictions should be made as the valve and engine designs progress. This information also should be used to update the analysis and evaluate the adequacy of the configuration.

3. The Conditions Imposed upon the Valve by Both Ground and Flight Testing shall be Specifically Considered in the Mechanical Design

Valve and engine test plans should be reviewed periodically to permit the analysis and configuration adequacy assessments to be updated. For example, prior to the obtaining of flight data the engine compartment temperatures for the Apollo SPS valve was considered to be a range of 30° to 140°F and testing requirements were established accordingly. The 140°F limit presented a possible design problem; however, actual flight data reduced this range to 30° to 110°F and the problem was eliminated.

III, A, Operating Conditions and Environment (cont.)

4. The Mechanical Design of the Valve shall be Integrated into the Engine and the Vehicle

Integration with higher assemblies should include definition of interface configuration, support and mounting, envelope requirements, as well as line loads and orientation. These should be controlled by an installation drawing defining interfaces as well as assembly and installation procedures.

5. The Design shall Include Consideration of the Effects of Possible Operation of the Valve Under Malfunction Conditions

The conditions considered should be based upon malfunction analysis of engine and valve testing, considering credible accidents, possible malfunctions, substitute fluids, kill parameters, and facility effects. The most widely known example of this consideration is the series-parallel design feature of the Apollo SPS bipropellant valve and other valves utilized on the Apollo Program. This design approach assures engine start in the event that one valve element fails to open and also assures engine shutdown if a valve element fails to close.

6. The Effect of Cavitation and Cavitation Damage upon the Valve shall be Included in the Design and Structural Analysis

Stress analysis and material selection should include the effects of loading as well as damage to the valve caused by cavitation if such methods are available. If they are not, an additional factor of safety should be considered.

III, Practical Development Problems and Solutions (cont.)

B. GENERAL REQUIREMENTS

1. Childown Procedures or Requirements shall be Considered when Selecting the Material and the Configuration as well as when Conducting Structural Analysis

The mechanical arrangement should be selected so that stresses and distortions are minimized, fits and pilots are retained, and attachment stresses kept within acceptable limits.

2. Critical Clearances and Small Passages shall Include Consideration of the Effect of Contamination Entering the Valve from the System as well as during Installation or Assembly

The design should be selected so that it is compatible with the expected contamination level.

3. Valve Installation Procedures shall be Considered during Interface Design

Adequate clearance shall be provided for bolts and nuts as well as protection for critical sealing surfaces.

4. Protection shall be Provided against Damage, Contamination, and Excess Moisture

Covers should be provided for damage, contamination, and moisture protection. Inert gas positive pressurization should be considered to protect valves from the effects of condensed and frozen moisture. Specific procedures should be defined on the assembly and installation drawings as well as on the handling and test documents. Inspection procedures should be defined for verification of this protection.

III, B, General Requirements (cont.)

5. Positive Means of Configuration Identification shall be Provided

Unique part numbers should be applied to all parts and non-interchangeable configurations of the same part. Serialization is recommended for all performance-sensitive or structurally-critical components.

6. Backwards Installation of the Valve shall be Prevented

Interface flanges of different configurations are recommended to prevent backwards installation.

7. Valve Maintenance shall be Considered during Initial Design

Seats and packings should be accessible. Maintenance of the valve should be possible with a minimum of parts removal and retest requirements. The use of lubrication and adjustments should be minimized and the use of special tooling should be avoided. Parts to be replaced during valve maintenance operation should be completely interchangeable.

8. Valve Deterioration from Operation shall be Considered

Seats and seals should be designed to minimize the effects of valve operation on sealing surfaces. The use of devices to avoid rubbing action on seals should be considered. For example, the use of cams to lift off a ball seal during the greater portion of ball rotation.

III, Practical Development Problems and Solutions (cont.)

C. STRUCTURAL INTEGRITY

1. Structural Integrity of all Components shall be Assured

To ensure structural integrity, it is recommended that the structural analysis include the following elements:

a. Limit load factors, pressure loads, inertia loads, side loads, and temperature, vibration, acoustic power input effects.

b. Identification and source of material design properties at operating temperature and other environmental conditions.

c. Weight breakdown, shear diagram, moment diagrams.

d. Component load breakdown indicating the combined critical loading conditions (axial, moment, shear) for each major component.

e. Handling, transportation, and assembly loads.

III, Practical Development Problems and Solutions (cont.)

D. ACTUATION SYSTEMS

1. Operating Conditions and Environment for the Actuator Shall be Derived from the Intended Usage and Becomes the Basis for the Actuator Design

The conditions that should be specified and included in the actuation system design and analysis are:

a. Basic method (hydraulic, pneumatic, electric)

b. Force requirements

c. Response requirements

d. Power requirements

e. Stroke

f. Locking requirements

g. Size and weight limitations

h. Repeatability requirements

i. Environment

E. HOUSING

1. Housings shall be Designed to Permit Repeated Assembly Without Damage or Loss of Piloting or Sealing Capability

Provision should be made for repair by thread inserts, remachining of critical surfaces, replacement of studs, and oversizing of ports. Tapers and chamfers should be used and tighter-than-necessary fits should be avoided.

III, E, Housing (cont.)

2. The Housing Configuration shall be Adequate to Accommodate Required Instrumentation Access

Wall thickness and space for bosses, probes, line routing terminals and brackets should be provided along with a capability for replacing them during testing.

3. Hydrostatic Proof Pressure shall be Based Upon the Operating Temperature Effect on Material Strength

Proof test pressure should be selected to produce stress levels similar to those expected during operation. Ambient test pressure of cold parts should be lower than operating proof pressure. Ambient test pressure of hot parts should be higher by the difference in permissible strength caused by temperature.

4. Proof Test Fixtures and Procedures shall be Designed to Carefully Simulate Loading so as to Prevent Excessive Stress of Unrepresentative Proof of Integrity

The fixture configuration and test procedures should be considered and analyzed as part of the housing design.

5. Leakage Testing of Housings shall Include Consideration of Propellant Effect as Compared with the Test Media (Weeping, Effect Upon Porosity)

For most propellants, dry air or dry nitrogen gas should be used as leakage test media for valves. Helium gas, with leakage detection by a halogen sniffer, should probably be used for hydrogen valves.

III, E, Housing (cont.)

6. Adequate Bearing Support Stiffness shall be Provided if the Valve Housing Serves as a Bearing or Bearing Carrier Mount

Housing stiffness should be evaluated as part of the housing analysis.

7. Non-Standard Instrumentation Bosses shall be Justified

It is recommended that instrumentation bosses be standardized to a 1/4 in. tube size, AN type configuration.

F. FITS AND CLEARANCES

1. Clearances and Fits shall be Analyzed under the Worst Combination of Temperatures Considering Assembly, Ambient Temperature or Space Soak, Chilldown Prior to or During Start, Thermal Equilibrium, and Shutdown as well as Soak-Back

A thermal analysis should be conducted based upon predicted duty cycles and test conditions. These thermal conditions then should be superimposed upon a stress analysis. Thus, the adequacy of fits and attachments can be assessed based upon the combined effects. Special configuration, or revised duty cycle, or test procedures can be required.

G. FASTENERS AND ATTACHMENTS

1. Locking Devices shall be Analyzed for Assembly-Induced Stress (i.e., Friction-Induced Shear in Lock Washer Tabs)

A very conservative analysis should be conducted to preclude shearing the tab retaining the washer to the stationary part. The face of the bolt or nut should be relieved to prevent axial contact and false torque, or

III, G, Fasteners and Attachments (cont.)

damage of the bolt or nut face by the sharp-edged washer tabs. Ductile material should be used.

2. Thread Lubricants shall be Verified for Propellant Compatibility

It is recommended that compatibility be confirmed by chemical tests.

3. Torque Values for all Bolt or Bolt/Nut Applications shall be Specified

The assembly drawing and build-up sheet should specify torque values. Also, critical torque values should be recorded as well as verified.

4. Adequate Wrench Clearance shall be Provided for all Attachments

Wrench clearances should provide space to accurately determine torque values; therefore, accessibility and non-awkward positioning for standard wrenches should be provided.

5. Use of Snap Rings shall be Justified

If snap-rings are mandatory, careful evaluation should be made of groove detail, installation procedure, material selection, and loading.

6. Preload shall be Precisely Controlled in Critical Attachments

A direct determination of preload is recommended. This should be done by measuring the increase in depth of a longitudinal hole in the bolt and comparing it to the desired preload expressed as strain.

III, Generalized Propellant Valve Design Criteria and Recommended Practices (cont.)

H. JOINTS AND STATIC SEALS

1. Flange Designs shall be Based upon Deflection as well as Stress Level

Flange analysis and bolting design should include the effect of pressure, mechanical and thermal loads, as well as preload tolerance caused by torquing, upon flange position and seal compression.

2. Bolt Joints shall be Analyzed for Bolt and Flange Thread Stresses Considering the Different Strengths of Bolt and Flange Material as well as the Variation of Preload as a Function of Torque

Through-holes and nuts or oversize high strength inserts are recommended if stresses in the flange are excessive. The bearing stresses should be verified as being acceptable.

3. Flange Joints shall be Designed and Analyzed as a Unit Consisting of the Flanges, Seals, and Bolts

The elastic deformation of the joint elements should be included in the analysis.

4. Damage to Flange Seal Surfaces shall be Avoided

Female flange pilots should be located on the valve interfaces to prevent damage during assembly and testing.

III, H, Joints and Static Seals (cont.)

5. Static Seal Selection and Design shall be Based upon an Accurate Assessment of the Actual Requirement and Capability

Manufacturer claims of performance should be carefully evaluated against the specific application. Tests in the correct environment are recommended prior to design commitment.

6. External Joints shall be Minimized for Maximum Reliability

Each joint should be evaluated for effect upon assembly sequence and reliability (measurements, visual access), manufacturing ease and cost, material availability, and inspectability.

7. Potential Leakage of a "Zero Leakage" Joint Requirement shall be Specially Considered

Welded joints and dual seals with inert buffer fluid pressurization or leakage bleed-off should be considered.

I. MATERIAL SELECTION

1. Materials shall be Chemically and Thermally Compatible with the Propellant and Other System Fluids

Material selection should be based upon the specific application, including all fluids (propellant, purge and cooldown, propellant simulant, nondestructive test), temperature (assembly, ambient or space soak, chill-down, equilibrium, soak-back), and other environments (radiation, storage, vacuum).

III, I, Material Selection (cont.)

2. Material Properties shall Satisfy the Pertinent Structural Requirements Considering Ambient and Operating Temperature, Environments, and Life

The appropriate strength parameter (e.g., yield, stress rupture, or fatigue allowables) should be determined and used as the basis of structural adequacy assessment.

3. Compliance of Mechanical Properties with Values Upon Which Integrity is Evaluated shall be Ensured

It is recommended that material for test bars be added to each forging. If not feasible to add this material in a high stress area, correlation of data from accessible positions should be combined with forging control and remote bars from each part to guarantee integrity.

4. Material shall be Compatible with the Appropriate Manufacturing Techniques

Manufacturing parameters (i.e., forgeability, machinability, weldability, and heat treat requirements), as well as cost should be evaluated.

5. Material Selection shall Include Consideration of Stress Corrosion Sensitivity and Environment

The environment and the conditions leading to stress corrosion, should be analyzed and susceptible materials avoided.

III, I, Material Selection (cont.)

6. <u>The Use of Exotic Materials that are Difficult to Fabricate and/or Expensive shall be Carefully Evaluated for Actual Benefits to be Derived in a Specific Application</u>

Alternative configurations, strength levels, and fabrication processes should be evaluated in terms of loss of performance or increase in weight.

J. FABRICATION METHODS AND INFLUENCES

1. <u>Casting shall be Evaluated as an Economic Means for Accomplishing Required Complex Shapes</u>

Strength and dimensional/finish ability of a casting should be evaluated against a machined configuration.

2. <u>Large, Heavy Castings shall be Provided with a Means for Handling</u>

Lifting and clamping pads or bosses that can remain in place throughout the fabrication sequence are recommended.

3. <u>Castings shall Incorporate Clear, Measurable Set-Up Surfaces to Properly Locate Machined Surfaces to Hydraulic Passages</u>

Dimensioning should be based upon identifiable, accessible datum planes and diameters.

4. <u>A Means for Ensuring Structural Integrity shall be Provided for Cast Configurations</u>

It is recommended that all housings be hydrostatically proof tested.

III, J, Fabrication Methods and Influences (cont.)

5. Configurations shall be Critically Examined to Ensure that the Manufacturing Process, Precision, and Cost are Justified

More liberal tolerances, finishes, and alternative configurations should be evaluated in terms of the loss of performance or increase of weight.

K. ASSEMBLY REQUIREMENTS

1. Provision for Checking Against Gross Assembly Errors (Parts not Bottomed, Installed Backwards, Left Out) shall be Provided

A build-up sheet is recommended to ensure recording of appropriate dimensions, torques, runouts, and serial numbers. Gross checks, including visual inspection, simple measurements, leak checks, and breakaway torque checks should be specified.

2. Blind, Hidden, or Inaccessible Traps that Cannot be Reliably Cleaned and Inspected shall be Eliminated

Thread inserts, intersecting holes, plugs, assembled bolts and fittings, as well as inaccessible cavities should be eliminated. If such items are mandatory, a reliable cleaning and inspection procedures should be devised.

3. Critical Clearances shall be Capable of Confirmation at Assembly

Direct measurement (rather than deduced dimension) and visual check are recommended. A build-up sheet with required dimensions and the method of measurement clearly specified should be used for recording and verification of clearance.

III, K, Assembly Requirements (cont.)

4. Leaks shall be Locatable During Assembly

Provision should be made for leakage checks at selected stages during the assembly cycle. Intermediate leakage checks (at low pressure if necessary for safety) prevent excessive reassembly effort and ease the isolation as well as location in the event of leakage.

5. Propellant Valves shall be Subject to Special Assembly Precautions

Propellant valves should be assembled in contamination-free Clean Rooms using "white glove" procedures. It is recommended that parts be especially protected following cleaning, especially prior to assembly rather than before storage as individual parts. Special handling procedures should be specified to guarantee freedom from contamination.

6. Contamination-Free Assembly Procedures shall be Utilized

Special Clean Room procedures are recommended for assembly to preclude contamination of critical parts of the valve.

IV. PROPELLANT VALVE EXPERIENCE REVIEW

As part of the Apollo SPS Valve Improvement Program a review of the bipropellant valve experience of the Aerojet-General, TRW Inc. and Bell Aerosystems Inc. organizations was conducted. All three of these companies are involved in the design, manufacturing and testing of bipropellant valves for the Apollo system. Problems which have been experienced in these programs are listed and discussed as to effects of design, manufacturing and test techniques.

A. SEAL LEAKAGE

Seal leakage is the most common problem in the design, manufacture and testing of bipropellant valves. It can be caused by a large number of factors. The most important of these are discussed below and related to most common causes.

1. Wear

Wear of a seal occurs when the seal is rubbed by a mating part. It can be the result of design, test conditions and actual use. It is primarily a function of the materials used and their surface finish, the unit loading on the seal-to-ball interface, the relative velocity of the seal and the ball, the effects of propellant on the seal material's properties, and the properties of any lubricants utilized. All three Apollo bipropellant valve Manufacturers experienced wear on the teflon ball seals in the form of flaking. These flakes would build up on the ball and subsequently scratch the seal or just hold it up off the ball and cause leakage. TRW combatted the problem by impregnating the seals with a lubricant, and reducing the velocity of rubbing during dry operation of the valve. AGC incorporated glass filled teflon seals to eliminate the wear. Bell eliminated their flaking due to wear by limiting the number of dry cycles that could be run on a valve at one time without

intervening wet cycles. Each of these approaches was adequate, however, each was also a compromise. The TRW approach resulted in the case of a lubricant not completely compatible with the propellants and a reduction of confidence in functional data. The AGC approach reduced the ultimate cycle life of the design, although this still remained within that required for the present application. The Bell approach placed additional limitations and costs on the program.

2. Seal Deformation

Seal deformation can result from the design of the seal not taking into account all loads imposed on the seal during operation, especially transient flow forces. It can also be the result of improper test conditions imparting higher than design loads on the seal.

3. Improper Contact Area and Load

Results from design and manufacturing. Once the proper contact area and load have been determined through analysis and test it is necessary to adhere to strict assembly and inspection procedures to achieve repeatable areas and loads.

4. Improper Seal-to-Ball Fit

Results from manufacturing tolerances. Aerojet controls by furnishing seals to the proper fit prior to installing the seal in the valve. Other manufacturers have cycle valves a number of times to "wear in" the seals and obtain proper fits.

IV, A, Seal Leakage (cont.)

5. Material Finishes

a. Ball Finish

Seal leakage has been caused by sharp edges on the ball and by "orange peel" finish on the ball. All three suppliers have determined that a number 4 finish is desirable. Aerojet also found that a finish of number 2 or better will result in excessive wear on the seal.

b. Seal Finish

Machining of the teflon seal must be carefully controlled to prevent teflon fibers "hanging on" which can get between the seal and the ball. These microscopic fibers can hold the seal off far enough to cause excessive leakage. Polishing has been an effective means of eliminating this problem when coupled with thorough flushing of the seal to remove loose material.

6. Handling Damage

Great care must be taken in all cleaning, transporting and assembly of the valve parts to protect sealing surfaces.

7. Shaft Deflection

Seals must be designed to follow shaft deflection under all design conditions including temperature and pressure transients. Excessive shaft deflection must be prevented by designing for deflection as well as stress in sealing members such as shafts, pistons, and flanges.

IV, A, Seal Leakage (cont.)

8. Propellant Salting

Once a valve has been exposed to propellants it must be adequately protected from air and moisture in order to prevent the generation of salts which can cause seal leakage. The valve should be designed to allow thorough draining, purging, and aspirating of the propellant and once propellants have been removed a positive pressure should be maintained in the propellant passages using dry gaseous nitrogen. This approach has been very effective on the Apollo SPS bipropellant valve.

B. ACTUATOR FAILURES

Actuator failures of different types was another problem area which was common to the three companies involved in the Apollo bipropellant valves. All of the problem types listed below were experienced by one or more of the three companies but not necessarily all three.

1. Actuator Piston Leakage

This type of leakage can be caused by a number of things.

a. In one case it was caused by rubbing of springs during actuation which generated contamination which subsequently got into the sealing area causing leakage. This type of failure can be prevented by providing clearances to prevent rubbing or providing a liner between the rubbing parts which will not allow generation of contaminants by rubbing.

b. In another case the leakage was caused by a combination of tolerances and the improper matching of thermal coefficient of expansion between the piston and the cylinder materials. This was the result of using

a Delrin piston head in an aluminum cylinder. The coefficients of thermal expansion were such that in order to assure clearance between the piston and cylinder at the maximum operation temperature the piston diameter was too small at the minimum operating temperature. This problem was corrected by incorporating an aluminum piston head with a thin Delrin guide ring to prevent galling between the two aluminum surfaces. In design worst case analysis must be made to determine interaction effects such as these.

c. Piston leakage can also be caused by galling of the piston in the cylinder. Design should ensure that no rubbing of similar materials occurs.

2. Actuator Force Margin

In designing valve actuators it is necessary to take into account all forces operating on the actuator and the system characteristics as well. For example, the early Aerojet valve was designed for actuation by fuel pressure. However, it was later found that the system fuel pressure fell so low during valve opening that the valve would not open smoothly or repeatably. Bell had trouble with cocking of the actuator piston and later had high friction from rolling and twisting of the piston O-ring. Both of these conditions contributed to a low actuator force margin.

C. VALVE PRESSURE DROP VARIATION

It is important for bipropellant valves to have repeatable pressure drop characteristics from valve to valve. This is extremely critical when the valve is phased to provide the proper fuel and oxidizer lead/lag relationship for the rocket engine. Variability in this parameter can result from tolerance stackups and from assembly errors in measuring installation and shimming dimensions.

V. BIPROPELLANT VALVE TRADE-OFF STUDIES

Once the engine system design parameters have been established it is possible to conduct a trade-off analysis to determine the type of valve and valve features which will best satisfy all of the requirements. As stated earlier this analysis is a systematic form of compromise wherein advantages and disadvantages of the different valve types are weighed against the specific requirements to permit an optional selection.

In order to conduct this trade-off it is also necessary to do preliminary design work with each of the valve types to be considered. Layouts on sketches of each design should be made along with design calculations to determine sizes, major stresses, weights, etc. Without this type of design work the trade-off must be done on generalities rather than hard facts for each of the particular designs.

Figure 3 presents the trade-off analysis conducted as part of the Apollo Bipropellant Valve Improvement Program. In this analysis the method of actuation was selected first. In this case the system judged to be most desirable from the technical viewpoint was rejected because of other system and program restraints. On the basis of all the requirements the pneumatic system was selected.

Next the basic type of valve was selected. Design layouts were prepared for all of the types listed. Again the selection was based to a large extent on system requirements rather than operating characteristics of the design themselves. In this case one of the most heavily weighted factors was the necessity to keep the flow characteristics as much like the present valve as possible.

The third major trade-off was the decision as to how the valve modules would be arranged. Here again design layouts were required to determine

V, Bipropellant Valve Trade-off Studies (cont.)

specific advantages and disadvantages of each concept. Finally the seal configuration was chosen again with the aid of design layouts and calculations to determine the travel vs lift curves for each.

No hard and fast rules or weighting factors can be given for trade-off analysis. Each case must be determined in the light of all possible requirements and constraints.

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Type	Sealing Capability Gas	Sealing Capability Liquid	Environmental Limitations	Size	Weight	Pressure Loads	Flow Rate and ΔP	Transient Characteristics	Cycle Life	Response	Actuation Forces
1. Poppet	3	3	3	3	3	3	2	3	3	3	3
2. Plug	3	3	3	3	3	3	2	3	3	3	3
3. Ball											
a. Liftoff	2	3	2	2	2	2	3	2	2	2	2
b. Rubbing	2	3	2	2	2	2	3	2	2	2	2
4. Butterfly	1	2	2	3	3	2	3	2	2	2	2
5. Blade	2	3	2	2	2	1	3	1	2	1	1
6. Gate	2	3	2	2	2	1	3	1	2	1	1
7. Diaphragm	3	3	1	3	3	1	3	3	2	2	2

3 = Excellent or highly favorable feature

2 = Good or favorable feature

1 = Poor or unfavorable feature

Characteristics of Valve Pipes

Figure 1

Type	Stroke	Locking	Speed	Force Output	Repeatability	Size
1. Pneumatic	2	2	2	3	1	2
2. Hydraulic	2	3	2	2	1	2
3. Electrical						
a. Solenoid	3	2	3	2	2	3
b. Motor	3	2	3	2	3	3
4. Explosive	3	2	3	2	2	3

3 = Excellent or highly favorable feature

2 = Good or favorable feature

1 = Poor or unfavorable feature

Actuator Characteristics

Figure 2

Method of Actuation

Type	Advantages	Disadvantages	Summary
Electrical	1. No seals required 2. Repeatable timing 3. Fewer components 4. No decontamination required	1. Does not meet present engine interfaces 2. Requires more development 3. Impact on system power requirements	The electrical actuation was selected as the most desirable type for an improved valve. However, due to the long and expensive development required it was determined that the work could not be accomplished within the constraints of the present program. On this basis pneumatic actuation was selected but the actuator design is to be made so that electric actuation could be applied at a later date with no modification required to the valves or valve housings.
Hydraulic	1. Uses propellant - no third fluid required 2. No limit on fluid available for actuations	1. Pressure decay during start transient requires large area piston and large volume of fuel. Decay can also result in erratic valve timing. 2. More cavities to be decontaminated.	
Pneumatic	1. High force margin available 2. Repeatable timing 3. No decontamination required 4. Meets existing interfaces. 5. Maximum utilization of SPS experience	1. Third fluid must be carried 2. Additional sealing required 3. Requires least development	

Bipropellant Valve Trade-off Chart

Figure 3, Sheet 1 of 7

Valve Configuration

Type	Advantages	Disadvantages	Summary
Ball	1. Retains same flow characteristics as present valve 2. Low pressure drop 3. Makes maximum use of previous experience 4. Can use two seals per ball	1. Lower sealing forces available 2. Wiping motion on seal reduces seal life	The ball type valve was selected with the primary factors in the decision being that hydraulic characteristics would be the same as the existing SPS valve and thus less engine transient testing would be required and secondly, the use of the ball valve assured maximum utilization of previous experience.
Poppet			
Cam Visor Type	1. Minimum wiping of seal 2. Low pressure drop 3. High seal loads 4. Inline flow porting for ease of redundant arrangement	1. One seal per position 2. High cam loads and bearing stresses 3. Complex mechanism 4. Different flow characteristics 5. High actuation forces required	
Toggle Visor	1. Minimum wiping of seal 2. Low pressure drop 3. High seal loads 4. Lower compressive stresses than cam mechanism	1. One seal per position 2. High actuation forces required 3. Complex mechanism 4. Different flow characteristics	

Bipropellant Valve Trade-off Chart

Figure 3, Sheet 2 of 7

Valve Configuration (cont.)

Type	Advantages	Disadvantages	Summary
Axial	1. High seal loads 2. Minimum wiping of seal 3. Least complex of poppet types.	1. High pressure drop 2. Different flow characteristics 3. High actuation force required.	
Blade	1. High sealing force 2. Low pressure drop	1. Different flow characteristics 2. Complex mechanism required to reduce seal wiping. 3. Limited experience with this type seal 4. Too heavy	

Bipropeliant Valve Trade-off Chart

Figure 3, Sheet 3 of 7

Redundancy Configuration

Type	Advantages	Disadvantages	Summary
Quad Mono-Propellant Valve Module	1. Permits assemble/disassembly of one valve without affecting another 2. Can be adjusted, cycled, and leak tested independent of other valves	1. Probable increased size and weight 2. Additional external leak paths 3. More interface alignment problems	The cartridge module approach was selected with the housing to be in the good monopropellant configuration. This combination provides the best accessability to individual modules and still requires the least space and fewest external seals.
Quad Bipropellant Valve Module	1. Any valve can be disassembled without disturbing another 2. May require fewer internal static seals than cartridge concept 3. Spacing between valve bores can remain same as SPS	1. Most complex of all types 2. Requires additional external static propellant seals for interface between the two valves and actuator units. 3. May not meet existing SPS injector and feedline interfaces	

Bipropellant Valve Trade-off Chart

Figure 3, Sheet 4 of 7

Redundancy Configuration (cont.)

Type	Advantages	Disadvantages	Summary
Single Mono-propellant Valve Module	1. Each module less complex than above types 2. Can be adjusted, cycled, and leak tested independent of other valves	1. Requires more flanges than cartridge concept 2. Probable increased size and weight 3. More interface alignment problems	
Cartridge Module	1. Most compact 2. Fewer flanges and static seals 3. Each valve mechanism is identical and is completely independent of one another. 4. Each cartridge will house and support both the ball and shutoff seals; therefore, cartridges can be assembled, cycled, and leak tested prior to assembly in valve housing. 5. Shaft seal problems are virtually eliminated by use of universal linkage between shafts of	1. Increased space required between the upper and lower bores and between the balls possibly requiring redesign of present injector and/or propellant feedline interfaces	

Seal Configuration

Type	Advantages	Disadvantages	Summary
Cam Lift	1. Good potential for considerable improvement of shutoff sealing capability due to axial lift motion of seal from ball. 2. By using this concept with the ball valve configuration, maximum utilization of SPS valve technology can be realized.	1. The high cam bearing stresses and sliding action of the cam may introduce severe materi material and contamination problems. 2. Cam mechanism may make cartridge larger due to space required for mechanism.	The cam lift seal configuration was selected for the primary reasons of least seal wiping, smallest space requirements and two seals can be used per ball.
Crank Lift	1. Good potential for considerable improvement of shutoff sealing capability due to axial lift motion of seal from ball. 2. Maximum utilization of SPS valve technology by use of ball valve. 3. Crank to link bearing stresses are low-no highly loaded metal-to-metal sliding contact is used.	1. More ball rotation required before seal is lifted away from ball than with cam lift. 2. Crank lift mechanism requires more space than mechanism.	

Bipropellant Valve Trade-Off Chart

Figure 3, Sheet 6 of 7

Seal Configuration (cont.)

Type	Advantages	Disadvantages	Summary
Eccentric Ball	1. Seal lift is accomplished with least amount of mechanical complexity. 2. Concept is adaptable to present SPS Valve Configuration.	1. More ball rotation required before seal is lifted away from ball than with other designs. 2. Valve positioning may be extremely critical since slight over-closure may damage seals and under-closure will not seal.	

Figure 3, Sheet 7 of 7

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